Comparing environmental flow scenarios from hydrological methods, legislation guidelines and hydrodynamic habitat models downstream of the Marathon Dam (Attica, Greece)

Christos Theodoropoulos1,2,*, Spyridon Georgalas2, Nikolaos Mamassis2, Anastasios Stamou2, Peter Rutschmann3, Nikolaos Skoulikidis1

1 Hellenic Centre for Marine Research, Institute of Marine Biological Resources and Inland Waters, 46.7km Athens-Sounio ave., 19013, Anavyssos, Greece
2 National Technical University of Athens, Department of Water Resources and Environmental Engineering, Iroon Polytechniou 5, 15780, Athens, Greece
3 Technical University of Munich, Chair of Hydraulic and Water Resources Engineering, Arcisstr. 21, D-80333 Munich, Germany

* Corresponding author:
Phone: +302291076335; E-mail: ctheodor@central.ntua.gr

Abstract - In their effort to balance anthropogenic water demand and ecosystem conservation within a sustainable water resources management framework, water managers and stakeholders need sound scientific guidance. In this study, we applied a two-dimensional hydrodynamic habitat model using benthic macroinvertebrates as the target aquatic community, and carried out an environmental flow (eflow) assessment downstream of the Marathon Reservoir (Attica, central Greece). Hydrology-based eflow scenarios were additionally developed over an 11-year period, and the lowest acceptable ecosystem-based eflow was compared with the hydrology-based environmental flow predictions. We found that the hydrological methods tend to under-estimate the eflows required to ensure functional aquatic ecosystems. The results showed that (i) the different hydrological methods developed highly variable eflow scenarios, ranging from 0.0006 m³/s to 0.18 m³/s, (ii) the ecosystem-based environmental flow was up to 183% higher than the hydrology-based ones and 26% to 465% higher than those defined by the national legislation and (iii) the probability of agreement between hydrological and ecological predictions was 12.5%, as only one out of the eight hydrology-based scenarios coincided with the ecosystem-based eflows. We conclude that hydrological methods should be used with caution in the absence of ecological information. Their use as stand-alone tools seems problematic and bears a high risk of producing inappropriate environmental flow scenarios. Integrative frameworks combining hydrological-ecological methods could be useful to provide information on what is ecologically-acceptable and hydrologically-socially feasible, but since the two methods comprise structurally-different, non-interacting concepts, they are inherently insufficient to increase the confidence of predicting and selecting environmental flows.

Keywords
- Tennant
- Ecosystem-based
- Hydrological
- Eflows
- Marathon
- Macroinvertebrates
1. Introduction

Environmental flows (eflows) describe the quantity, timing, and quality of the water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007). During 40 years of research, more than 200 methods for assessing environmental flows emerged worldwide (Tharme, 2003) and have been recently categorized in three groups depending on the type of data they use to calculate eflows: (i) hydrological methods, which assess environmental flows based on long-term historical hydrological information (Tennant, 1976; Richter et al., 1996), (ii) habitat simulation (also known as hydraulic/hydrodynamic habitat modelling) methods, which develop environmental flow scenarios based on the interaction between habitat suitability-availability and the distribution of aquatic biota (Vezza et al., 2015; Leitner et al., 2017; Koutrakis et al., 2018; Theodoropoulos et al., 2018a) and (iii) holistic methods, which combine hydrological and hydroecological/habitat information to define environmental flows for multiple biotic elements of the aquatic ecosystem (WFD CIS, 2015), including fish, benthic macroinvertebrates, aquatic and riparian vegetation (King et al., 2008; Poff et al., 2010; Solans and Jalón, 2016).

The most widely applied hydrological methods have been, *inter alia*, the Tennant method (Tennant, 1976) and the Indicators of Hydrologic Alteration (IHA - Richter et al., 1996). The Tennant method calculates eflow as a percentage of the average annual flow, based on specific eflow classes provided by Tennant (1976). The IHA method applies more complex hydrological indices including annual minimum and maximum flows, magnitude, frequency and duration of high and low flow pulses etc. and calculates/predicts multiple environmental flow components rather than just a baseflow, thus defining a variable annual environmental flow regime, instead of a fixed annual eflow value. These ‘desktop’ approaches require low effort (regarding time, costs and data processing) to be implemented and have long been preferred over the other two groups when long-term hydrological information is available.

While hydrodynamic habitat models have long been researched worldwide, their real-life applications have not been as popular as their hydrology-based alternatives. These methods quantify and predict the response of aquatic biota to gradients of hydraulic-habitat alteration. Typically, a hydrodynamic module provides information on the change of physical habitat as a function of discharge by predicting water depths (D) and depth-averaged flow velocities (V) at multiple flow rates in a computational mesh, which simulates the area under investigation (Theodoropoulos et al., 2015). A coupled habitat module compares the predicted values of V and D with information on the habitat preferences of aquatic biota to calculate habitat suitability at each simulated discharge (Acreman and Dunbar, 2004; Gopal, 2013). Environmental flow scenarios are developed based on the interaction between habitat alteration and ecological response.

Focusing on the hydrological and habitat simulation methods, both groups have been criticized for various aspects of their practical application. Hydrology-based methods lack ecological validation (Acreman and Dunbar, 2004) and thus, their credibility to provide ecologically appropriate flow regimes has often been questioned (Linnansaari et al., 2013). On the other hand, habitat simulation methods require considerable amount of fieldwork and relevant expertise to be successfully implemented (Linnansaari et al., 2013), while the fundamental concept on which these methods are based (the relationship between the instream flow-or habitat- and the abundance or biomass of aquatic organisms) has also been questioned (Moyle et al., 2011). Recently in Europe, and as Caissie and El-Jabi (2003) had previously concluded, the Guidance Document No. 31 (WFD CIS, 2015) supporting the Water Framework Directive 2000/60/EC (WFD - European Union Council, 2000), suggested a three-tiered hierarchy of the eflow methods’ application, depending on the detail/accuracy of the eflow prediction required and on the magnitude of the (possible) hydrological alteration due to the upstream water use (e.g. small-scale water abstraction or the presence of a large water-supply dam). However, environmental flows have often been calculated using only hydrological methods (e.g. Ye et al., 2012; Efstratiadis et al., 2014; Fuladipanah et al., 2015; Chen and Weisbrod, 2016), while studies implementing and
comparing eflow scenarios based on a combination of different methods in the same study area are limited (Li et al., 2009; Davis and Hirji, 2003; Shokoohi and Amini, 2013; Papadaki et al., 2017; Nikghalb et al., 2016; Tare et al., 2017; Stamou et al., 2018).

The purpose of this study was to develop and compare hydrological and ecosystem-based environmental flow scenarios downstream of the Marathon Reservoir (Oinoi Stream, Attica, Greece). We developed five eflow scenarios from three hydrology-based methods, and three scenarios based on the requirements of the national legislation. A two-dimensional hydrodynamic habitat model (HHM) was applied to develop ecosystem-based environmental flows using freshwater macroinvertebrates as the target aquatic community. Our main questions during implementation were the following:

i. Does the application of HHM-based environmental flow assessments yield similar eflow recommendations to the hydrological methods?

ii. Could the hydrology-based methods be applied as stand-alone methods, thus avoiding the costs and time required to apply the ecosystem-oriented HHM-based methods?

With reference to previous literature, we further discuss on the possibility of integrating the two approaches to increase the confidence on predicting and selecting environmental flows. As the anthropogenic pressure on the global freshwater resources is continuously increasing and climate-change-induced droughts intensify, the provisioning of accurately assessed environmental flows is of paramount importance; this study contributes to this direction for maintaining functional aquatic ecosystems in hydrologically altered river reaches.

2. Materials and methods

2.1. Study area

The study area is located in the Region of Attica (central Greece) (Fig. 1), downstream of the Marathon Reservoir, where a 54-m high concrete dam concentrates the inflows from the Charadros and Varnavas streams, and supplies drinking water to the city of Athens and the adjacent areas. The two streams share a common catchment area of 118 km$^2$, converging at the Marathon Dam and forming the Oinoi Stream, which empties in the Aegean Sea after a distance of approximately 10 km.

The area has a temperate Mediterranean climate characterized by mild winters and hot, dry summers. The mean annual minimum and maximum temperatures are 5 ºC and 29 ºC, reaching below 0 ºC and above 33 ºC during extreme winter and summer events, respectively. The mean annual precipitation is low, compared to the one recorded in the western and northern parts of the Greek territory (567 mm over a 70-year period). July, August and September are the driest months of the year.

The Oinoi Stream initially flows through a mixture of sclerophyllous vegetation and coniferous forests, which is gradually replaced by agricultural land and urban areas after a distance of almost 6 km. The stream afterwards passes through the town of Marathon, being surrounded by complex cultivation patterns and urban areas until it empties in the Aegean Sea. The water flow downstream of the dam is ungauged. The Marathon Dam was built in 1929 without an environmental flow valve and consequently, there is no outflowing water in the Oinoi Stream. Currently, the minor quantity of spring-fed water flowing through the stream is pumped for irrigation, leaving no flow in the river for almost throughout the year.
2.2. Hydrological data and hydrology-based environmental flows

In the absence of a gauging station upstream and downstream of the Marathon Reservoir, daily data from the operation of the Marathon Dam were obtained for an 11-year hydrological period (2002-2013) from the Athens Water Supply and Sewerage Company (EYDAP S.A.). These daily data were used to calculate the inflowing water discharge from the upstream watershed (Charadros and Varnavas streams converging upstream of the reservoir) and they included (i) reservoir water level fluctuation, (ii) precipitation, (iii) lake evaporation, (iv) the water volume transferred from the reservoir to the city of Athens. Similarly to Efstratiadis et al. (2014), a water balance model was developed and applied to the aforementioned data; the inflows considered were the water discharge from the upstream watershed and the daily volume of precipitation, and the outflow was the water volume abstracted for the Athens drinking water supply.

The calculated daily discharges from the Varnavas and Charadros streams inflowing to the dam for the period 2002 - 2013 were considered as the natural river flows (the mean monthly discharge values are shown in Fig. 2) from which the hydrology-based environmental flows were calculated using the following methods:

i. Tennant method (Tennant, 1976); in this method, mean annual flows for each hydrological year are calculated and the average value for the whole period of study (QAA) is derived. Environmental flow
scenarios are afterwards developed based on the percent deviation from QAA. Based on the method’s recommendations, we considered the 10% QAA, 20% QAA and 30% QAA values as potential environmental flow candidates, reflecting the ‘fair’, ‘good’ and ‘excellent’ categories provided in Tennant (1976).

ii. Lyons method (Bounds and Lyons, 1979); this method uses monthly median flow (MMF) values, derived from long-term hydrological records, to develop monthly flow recommendations, weighted between wet and dry periods of the year. Based on the method’s requirements, we considered 60% MMF as the minimum environmental flow for the period between March and September, and 40% MMF as the minimum eflow during October-February.

iii. Basic Maintenance Flow (QBM - Alcácer-Santos, 2004); the QBM method analyses the variation in the distribution of minimum flows that have occurred for time periods ranging from one to one-hundred consecutive days (in total, 100 intervals). A moving average of daily flows is calculated for each interval, and the minimum value of each interval and for each year is afterwards derived. The relative increment between each pair of consecutive minima is calculated using the following equation:

\[ b^k_i = \frac{q^k_i - q^{k-1}_i}{q^{k-1}_i} \]

where

- \( b^k_i \) is the relative increment for the \( i^{th} \) year and for the \( k^{th} \) interval
- \( q^k_i \) is the minimum flow value of the \( k^{th} \) interval for the \( i^{th} \) year

The minimum flow value with the highest relative increment \( q^{k_{\text{max}}} \) is selected for each year and the average value of all \( q^{k_{\text{max}}} \) is the final environmental flow.

![Fig. 2. Mean monthly inflows to the Marathon Reservoir for the years 2002-2013, calculated based on a water balance equation.](image-url)
2.3. Environmental flows based on the Greek legislation

According to the requirements of the Greek legislation, three environmental flow scenarios were developed for the 11-year study period, based on the following: (a) 30% of the mean monthly flows of June, July and August, (b) 50% of the mean monthly flow of September, (c) 0.03 m$^3$/s minimum acceptable flow when the previous values are lower.

2.4. Hydrodynamic modelling

2.4.1. Topographic data

A 370-m long reach (3731 m$^2$) was simulated using a two-dimensional (2D) hydrodynamic model. We mapped channel topography with 459 points recording longitude (X), latitude (Y) and bottom elevation (H). A Real-Time Kinematic (RTK) GPS was used, consisting of the ‘Spectra Precision SP60 GNSS Receiver’ (http://www.spectraprecision.com/eng/sp60.html) and the ‘MobileMapper 10 GIS - GPS Receiver’ (http://www.optron.com/spectra/products/Mobile-Mapper-10.html). Slope breaks and areas with rapid relief changes were mapped with higher density of points, while fewer points where allocated in flat surfaces. The Blue Kenue software (http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/blue_kenue_index.html) was then used to import the topographic X, Y, H data and linearly interpolate channel topography, generating a triangular computational grid composed of 3,938 nodes and 7,140 triangular elements with a 0.9 m spatial resolution. In the rarely occurring cases where dense canopy cover restricted the communication between the RTK-GPS and the satellites (and consequently, spatial coordinates could not be accurately acquired), relief changes were manually measured from the nearest accurate point measurement (measuring the change in X, Y and H) and the missing points were manually inserted to the topography file in the BlueKenue software.

2.4.2. Hydrometric data, calibration and validation

Two surveys at different discharges (Q), commonly occurring in the study reach, were carried out to calibrate and validate the hydrodynamic simulation. The model was calibrated using the data from the first hydrometric survey (Q = 0.03 m$^3$/s) and validated using the hydrometric data from the second survey (Q = 0.3 m$^3$/s). Following a 2D-adapted, widely applied approach (Leclerc et al., 1995; Lee et al., 2010; Lin et al., 2015), and using the Swoffer 2100 current velocity meter (http://www.swoffer.com/products.htm) we measured water depths (D) and depth-averaged flow velocities (V) at 0.6 x D when D ≤ 0.75 m, and by averaging 0.2 x D and 0.8 x D when D > 0.75 m, based on Nolan and Shields (2000). These field measurements of V and D were recorded at 15 randomly selected points across the river reach at each survey. Longitude and latitude coordinates (using the RTK-GPS) were additionally recorded for each point and the two datasets were afterwards imported into the BlueKenue software. Calibration and validation were applied by manually adjusting the Manning’s roughness coefficient (n), based on an initial visual field estimation of the type of substrate, until an acceptable combination of R$^2$ values between the predicted and observed V and D was achieved. Specifically, the study area was divided in three sections and the Manning’s n in the validated model was 0.035 in the upper part, 0.05 in the mid-reach and 0.07 in the downstream part (Fig. 1). The R$^2$ between the predicted and observed D and depth-averaged V values was greater than 0.9 and varied from 0.9577 for D to 0.9795 for V (p<0.01) in the calibration dataset and from 0.8954 for D to 0.9591 for V (p<0.01) in the validation dataset (Fig. 3), suggesting strong, statistically significant correlations and an acceptable model performance. The validated model was used to simulate 16 discharge scenarios ranging from 0.01 m$^3$/s to 5 m$^3$/s.
2.4.3. Hydrodynamic simulation

The TELEMAC-2D v6.2 (Galland et al., 1991) was used to simulate D and depth-averaged V in various discharge scenarios. Prior to running the hydrodynamic simulation, boundary and initial conditions were defined using the FUDAA-PREPRO pre-processor (http://prepro.fudaa.fr). Q was prescribed at the upstream boundary and water surface elevation (Z) was prescribed at the downstream boundary, according to the software’s requirements. The TELEMAC-2D code applies the finite element method (Hervouet, 2007; Liu and Quek, 2014) to solve the depth-averaged St-Venant equations (conservation of mass, x-wise momentum, y-wise momentum).

We simulated D and depth-averaged V values in 16 discharge scenarios. Apart from the upstream inflow boundary, no other sources of incoming water exist in the study reach and, taking into account the short channel length (370 m) and the geology of the reach, no ‘sink terms’ were introduced in the model, assuming a constant discharge at the whole length of the study reach. Each simulation was run until a steady state was reached; the V and D values at each Q scenario (steady state) were afterwards used as inputs to the habitat model.

2.4.4. Habitat suitability modelling

In the absence of well-established fish communities in the Oinoi stream (possibly due to the extreme long-term hydrological alteration caused by the presence of the upstream reservoir), we used benthic macroinvertebrates (BM) as our target aquatic community, which have been found to be more widely distributed (Monk et al., 2006) and are commonly used in such cases elsewhere (Waddle and Holmquist, 2013). Their habitat preferences were acquired from the benthos-GR dataset (Theodoropoulos et al., 2018a), which

![Fig. 3. Correlation between the simulated and observed data (V: flow velocity, D: water depth) in 15 randomly recorded points during calibration and validation. Dotted lines represent 100% accuracy (observed values = simulated values).](image-url)
consists of 380 microhabitat observations sampled in Greek streams and rivers of similar environmental and hydraulic properties. The benthos-GR dataset calculates habitat suitability (K) using benthic-community metrics (No. of families, No. of Ephemeroptera-Plecoptera-Trichoptera families, Shannon-Wiener diversity and total community abundance) rather than just the abundance of individual taxa, thus describing the habitat suitability of the whole benthic-invertebrate community.

The dataset was used to train and cross-validate a fuzzy Bayesian algorithm (FRB), described in detail in Theodoropoulos et al. (2018a) and implemented using the HABFUZZ software (Theodoropoulos et al., 2016). In the FRB, the numerical inputs of V and D are converted to overlapping, five-class, trapezoidal-shaped membership functions (called fuzzy sets). The K values are also classified; in our case we used five, non-overlapping suitability classes (0 ≤ bad ≤ 0.2; 0.2 < poor ≤ 0.4; 0.4 < moderate ≤ 0.6; 0.6 < good ≤ 0.8; 0.8 < high ≤ 1). Each numerical input value of V and D is assigned to one or more fuzzy sets with a membership degree between zero and one (in our application, the type of substrate was treated as a crisp input and classified based on Schneider et al. (2010)). The training dataset (benthos-GR), with a priori calculated K values, is used to develop sets of data-driven IF-THEN rules, relating the input fuzzy sets with a specific K class. The fuzzy membership degree (MD) of each input variable (V, D and S) is considered as the probability of occurrence of the particular fuzzy set, such as “IF V is low with a membership degree of 1 AND D is moderate with a MD of 1 AND S is gravel with a MD of 1 THEN K is high with a MD of 0.3 and good with a MD of 0.7.” The IF-THEN rules are then combined using the Bayesian joint probability, so that (referring to the previous example) the probability of the specific microhabitat’s K being high is the joint probability that V is low AND D is moderate AND S is gravel AND K is high (1 x 1 x 1 x 0.3 = 0.3), while the probability of K being good is the joint probability that V is low AND D is moderate AND S is gravel AND K is good (1 x 1 x 1 x 0.7 = 0.7). Based on a utility function (Brookes et al., 2010), a score is assigned to each K class (bad: 0.2, good: 0.4, moderate: 0.6, good: 0.7, high: 0.9) and the habitat suitability for each microhabitat is predicted using the following equation:

\[ K = \sum M_{ij}S_{ij} \]

where,
K is the predicted habitat suitability
M_{ij} denotes the joint probability of occurrence of each \( \kappa \) class
S_{ij} denotes the score of each \( \kappa \) class

For the previous example, K equals to 0.7 x 0.9 + 0.3 x 0.7 = 0.84 (high).

We applied a ten-times-repeated ten-fold cross validation process (Kohavi 1995), in which the initial dataset was randomly partitioned in ten equal-sized subsamples. Nine subsamples (90% of data) were used as the training dataset and the remaining subsample (10%) was used for model validation. This procedure was repeated ten times (folds), using a different subsample for validation at each iteration. The whole 10-fold iterations were repeated ten times to acquire more robust results. The performance of the cross-validated habitat model (calculated as the average percentage of correctly classified instances (CCI) between each iteration of the ten-fold cross-validation process) was 61.2% (min: 58.95%; max: 64.1%).

The output of the hydrodynamic model (D and depth-averaged V values) at each simulated discharge was used as input to the habitat model, which calculated K at each node of the computational grid of the hydrodynamic model (resulting in 3938 K values x 16 discharge scenarios). The habitat suitability of the study reach at each Q was visualized using the Blue Kenue software.
2.4.5. *Environmental flow selection*

Following the approach of Theodoropoulos et al. (2018a), the optimal ecosystem-based environmental flow scenario was selected based on the combination of the following indicators-variables:

i. **Overall Suitability Index (OSI):**
   \[
   OSI = \sum_{i=1}^{w} K_i
   \]

ii. **Average OSI (nOSI):**
   \[
   nOSI = \frac{OSI}{w}
   \]

where,
   - \( K_i \) (from 0 to 1) denotes the habitat suitability
   - \( w \) denotes the total No. of wetted nodes in the computational grid at each Q scenario

iii. **Certainty of prediction (COP):** The ratio of the No. of microhabitat combinations actually found in the training dataset to the total No. of nodes in the computational grid; HABFUZZ applies a trick when a microhabitat combination is not found in the training dataset and instead of returning some arbitrary K value for a particular node (e.g. -1), it uses the K value of its neighboring node in the domain.

iv. **Percentage of wetted nodes in the computational grid at each Q scenario (w).**

v. **Habitat connectivity (C):** The ratio of connected (neighboring) nodes with \( K \geq 0.6 \) to the total number of wetted nodes with \( K > 0.6 \).

vi. **Habitat availability (A):** The ratio of connected (neighboring) nodes with \( K > 0.6 \) to the total number of nodes in the study reach (wetted and dry).

The optimal combination of the indicators was numerically expressed for each simulated Q using the Optimal Flow Scenario index (OFS):

\[
OFS = nOSI \cdot w \cdot C \cdot A \cdot COP
\]

All OFSi values were normalized in a 0-1 scale by dividing each OFSi with the maximum OFS observed. As the environmental flow is usually a negotiated value (Dyson et al., 2003), in addition to the best Q scenario, evaluated according to the maximum calculated OFS value, a 5-class system was applied based on the status classification system of the Water Framework Directive 2000/60/EC including the following classes; bad (0 ≤ OFS ≤ 0.2), poor (0.2 < OFS ≤ 0.4), moderate (0.4 < OFS ≤ 0.6), good (0.6 < OFS ≤ 0.8) and high (0.8 < OFS ≤ 1). A polynomial curve was applied to encompass the OFS values. Based on the polynomial function, environmental flow scenarios with OFS values higher than 0.6 (good and high classes) were considered acceptable and, therefore, potential ecosystem-based eflow candidates in possible negotiation schemes between scientists, stakeholders and managers.

3. **Results**

3.1. *Hydrology-based environmental flows*

The results of the hydrology-based environmental flow calculations are depicted in Fig. 4. According to the Tennant method, the mean annual flow for the 11-year period was 0.61 m$^3$/s, and the ‘fair’, ‘good’ and ‘excellent’ classes were 0.06 m$^3$/s, 0.12 m$^3$/s and 0.18 m$^3$/s, respectively. Due to the high number of consecutive days with extremely low flows or zero values, the Lyons and QBM methods yielded the lowest
environmental flow values (0.0006 m$^3$/s and 0.011 m$^3$/s, respectively). Varying outcomes ranging from 0.03 m$^3$/s to 0.135 m$^3$/s were obtained based on the requirements of the Greek legislation.

### Table 1

<table>
<thead>
<tr>
<th>Q (m$^3$/s)</th>
<th>OSI</th>
<th>nOSI</th>
<th>w (%)</th>
<th>C (%)</th>
<th>COP (%)</th>
<th>A (%)</th>
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<tr>
<td>0.01</td>
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<td>0.671</td>
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</table>

Q: discharge, OSI: overall suitability index, nOSI: average OSI, w: wetted nodes, C: habitat connectivity, A: habitat availability, COP: certainty of prediction

3.2. Ecosystem-based environmental flows

The depths in the wetted nodes of the study reach (data not shown) ranged from 0 m to 0.52 m for the lowest discharge (0.01 m$^3$/s) and from 0.1 m to 1.23 m for the highest discharge simulated (5 m$^3$/s). Depth-averaged V values, respectively ranged from 0 m/s to 0.59 m/s (Q = 0.01 m$^3$/s) and from 0.1 m/s to 3 m/s (Q = 5 m$^3$/s).

The simulated habitat suitability (K) values at each node of the computational grid and at each Q scenario are depicted in Fig. 5. According to the results, maximum habitat connectivity (C), availability (A) and
nOSI values were recorded at Q = 0.5 m³/s (Table 1), indicating this value as the optimal environmental flow (Fig. 6). Based on the WFD classification scheme however (Fig. 6a), in combination with the polynomial curve fitted (Fig. 6b), Q values ranging from 0.17 m³/s to 1.5 m³/s can be considered acceptable (OFS > 0.6; good-high WFD classes). The highest OSI was observed in Q = 1.1 m³/s, followed by 0.9 m³/s and 1.5 m³/s. The highest nOSI and habitat connectivity values were calculated for Q = 0.5 m³/s, 0.3 m³/s and 0.2 m³/s respectively. As expected, more wetted nodes were recorded in higher discharges, while habitat availability peaked at Q = 0.5 m³/s, followed by 0.7 m³/s and 0.3 m³/s.
Fig. 5. Habitat suitability values for each simulated discharge scenario. Values higher than 0.6 are considered acceptable according to the requirements of the Water Framework Directive 2000/60/EC.
4. Discussion

4.1. Environmental flows in the Oinoi Stream

The results of the study suggest that ecosystem-based environmental flows ranging from 0.17 m$^3$/s to 1.5 m$^3$/s are appropriate for maintaining functional benthic-invertebrate communities downstream of the Marathon Reservoir (Fig. 6). In lower and higher discharges, respectively, habitat suitability becomes unacceptable based on the requirements of the Water Framework Directive 2000/60/EC, and as a result, the long-term ecological integrity and functionality of the BM communities may be compromised. The aforementioned information could be a valuable reference in negotiations between scientists, water managers and stakeholders (Acreman and Dunbar, 2004), in their effort to balance anthropogenic water demand and ecosystem conservation, within a sustainable water resources management framework (Loucks, 2000).

4.2. Comparison between hydrological methods and HHMs

Theoretically, based on the ecological results, a variety of discharges ranging from 0.17 m$^3$/s to 1.5 m$^3$/s, could be considered appropriate for benthic-invertebrate communities. In practice however, water managers and stakeholders would probably select $Q = 0.17$ m$^3$/s as the optimal baseflow, being the lowest discharge capable of maintaining an acceptable ecological status of the aquatic ecosystem according to the WFD requirements. In contrast, according to the hydrological results, this value was among the highest calculated eflows; the hydrology-based environmental flows ranged from 0.0006 m$^3$/s according to the Basic Maintenance Flow method, to 0.18 m$^3$/s based on the 30% QAA (‘excellent’ class) of the Tennant method, while according to the national legislation, the environmental flow in the Oinoi Stream should range between 0.03 m$^3$/s and 0.135 m$^3$/s.

Nearly all hydrological methods applied, including the most popular Tennant method (Tennant, 1976), calculated lower environmental flows than the ones required to ensure ecosystem integrity and functionality according to the HHM-based, ecosystem-oriented approach followed in our study. Previous comparative studies in various reaches (Shokoohi and Amini, 2013; Nikghalb et al., 2016; Stamou et al., 2018; Theodoropoulos et al., 2018b) showed similar trends (but see Papadaki et al., 2017); Nikghalb et al. (2016) used the habitat preferences of *Luciobarbus capito* and calculated 3-fold increased environmental flows in comparison to those calculated using the Tennant method. Stamou et al. (2018) used the habitat preferences of *Squalius peloponensis* and calculated eflows two times higher than the hydrology-based eflows, and ten times higher than those required by the Greek legislation on environmental flows. Theodoropoulos et al. (2018b) used benthic macroinvertebrates and calculated environmental flows three times higher, compared...
to those required by the Greek legislation. However, in the comparative study of Papadaki et al. (2017) carried out in two sites in Greece, the optimal hydrology-based environmental flows in the first site were between 29% and 45% lower than the habitat-based eflows, while they were between 50% and 58% higher in the second site. Based on the results of our application and as nearly all previous studies suggest lower hydrology-based eflows, compared to the ecosystem-based methods, we could infer that hydrological methods often tend to under-estimate the environmental flows required to ensure healthy aquatic ecosystems.

4.3. Using hydrological methods in the absence of ecological information

Based on the aforementioned, the hydrology-based environmental flows in our study were lower than the lowest acceptable ecosystem-based environmental flow. Only the 30% QAA eflow of the Tennant method (0.18 m$^3$/s) coincided with the ecosystem-based eflow of 0.17 m$^3$/s (one out of eight hydrological scenarios - 12.5% probability of agreement). However, since the 30% QAA value reflects excellent ecosystem status based on the Tennant method’s recommendations, in the absence of a respective ecosystem-based study, water managers and stakeholders would probably prefer to apply the 20% QAA or the 10% QAA scenario, corresponding to the good and fair status respectively. Therefore, hydrological methods should be used with caution, when ecological information is not available. Since a thriving benthic-invertebrate community in the Oinoi Stream is ensured in Q = 0.5 m$^3$/s, delivering environmental flows based solely on hydrological methods would probably (with a probability of 87.5%) stress the benthic community to unsustainable levels. These results are in accordance with previous literature questioning the use of hydrological methods as stand-alone EFAs (Acreman and Dunbar, 2004; Linnansaari et al., 2013; Arthington 2012; Papadaki et al., 2017), while, in their case study, Shokoohi and Amini (2013) reached the same conclusion, suggesting that delivering hydrology-based environmental flows would degrade the aquatic ecosystem in the long term.

4.4. Integrating hydrological and habitat modelling methods

It has been widely acknowledged that integrated frameworks, incorporating hydrological methods in HHM-based EFAs, could be a valuable option when different stakeholders attempt to communicate within an environmental flow assessment (Arthington, 1998; Linnansaari et al., 2013). A three-tiered hierarchy including hydrological, holistic and hydrodynamic habitat modelling methods has been recently proposed in the Guidance Document No. 31 of the Water Framework Directive 2000/60/EC (WFD CIS, 2015), and as Stamou et al. (2018) conclude, integrated methods could result in more ‘realistic’ eflow values based on the historical hydrological conditions of the study area and considering what can be ‘socially’ delivered. This conclusion however should not be misconceived as ‘downgrading the ecosystem-based environmental flows to maximize possible short-term human benefits in the upstream’ (Homa et al., 2005; Jager and Smith, 2008). Acreman (2016) indicates that the desired future condition of an ecosystem depends on what a society considers acceptable; the society-based ecosystem condition however, should not be much deviating from the ecosystem-based standards to ensure long-term ecosystem functionality.

Within this concept, integrated hydrological-HHM frameworks may be useful for providing detailed reference on what is ecologically acceptable and hydrologically-socially feasible (Stamou et al., 2018), and for delivering environmental flows, which partially meet the needs of everyone and fully meet the needs of no one (Pitt and Kendy, 2017). However, the concept of integrating itself requires further explanation, as there is actually no way to literally integrate the two methods; as our application showed and the previous literature indicates, hydrological methods provide historical hydrological information on a study area, whereas HHM-based methods use the habitat preferences of aquatic communities to develop ecosystem-based environmental flow scenarios. Consequently, the use of integrative frameworks combining hydrological and ecological methods bears an inherent insufficiency to increase the confidence on predicting and selecting
environmental flows since they comprise different, non-interacting concepts. Nevertheless, as Stamou et al. (2018) imply, information from different sources (hydrological and ecological) is a useful basis for scientists, water managers and stakeholders towards the development of socially-accepted and ecologically appropriate environmental flow recommendations.

5. Conclusion

The results of the study show that different environmental flow methods can yield different eflow predictions, suggesting a specific trend, which was further supported by most previous studies available; that hydrological methods tend to under-estimate the actual environmental flows required to maintain functional aquatic communities. To answer our initial research questions:

1. **Does the application of HHM-based environmental flow assessments yield similar eflow recommendations to the hydrological methods?**
   Probably not; the results showed that except for one hydrological eflow scenario (30% QAA - Tennant method) the lowest acceptable ecosystem-based environmental flow was higher than the hydrology-based environmental flows, with varying deviation depending on the hydrological method followed. This is translated to a coincidence probability of 20% (one agreement out of five hydrology-based scenarios), being reduced to 12.5% if we additionally include the results of the Greek legislation guidelines.

2. **Could the hydrology-based methods be applied as stand-alone methods, thus avoiding the costs and time required to apply the ecosystem-oriented HHM-based methods?**
   Probably not; the hydrology-based methods should not be applied as stand-alone methods, as the risk of delivering ecologically-unacceptable environmental flows is high (with a probability of 80% to 87.5% based on the results of the study). This has also been highlighted in previous literature and further confirmed in our study, which showed that the ecosystem requirements may be slightly, but also highly different.

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